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Modelling of Micromachined Klystrons for Terahertz Operation

Robert E Miles. Joan Garcia, John R Fletcher, D Paul Steenson, J Martyn Chamberlain, Christopher M Mann, Ejaz J Huq

Abstract-- **The use of silicon and ultra-thick photoresist micromachining for the fabrication of terahertz frequency klystrons is discussed and a Monte Carlo based model of the device physics is presented. The model is shown to be an accurate representation of the electron flow in the device and it is demonstrated how it can be used as a design tool to optimise the geometry and operating conditions. An estimate of the power levels to be expected by the proposed devices is given.**

Index Terms-- Klystron, terahertz, micromachining

I. INTRODUCTION

The klystron is a high frequency vacuum tube device, originally developed in 1939 [1] by the Varian brothers and derived from the Heil Tube of 1935. Sixty years on klystrons are still in production for uses such as radar where high power (kW) microwave radiation is required and as millimetre wave oscillators. However, as the frequency of operation increases, the device dimensions progressively decrease and their manufacture by conventional machining becomes ever more difficult. The advent of micromachining techniques in both silicon and ultra-thick photoresists now puts us in command of a precision technology which we are using to scale down the dimensions of the klystron for operation at terahertz frequencies. The klystron is nevertheless a "transit time" device (see below) and in common with other such devices (e.g. field effect transistors, FETs) the power is expected to fall off with increasing frequency. However, the klystron has a larger conducting cross section than the FET giving higher current levels and consequently more power than the solid state device and therefore a useful power level in the region of 1 mW at THz frequencies is expected.

There are a number of trade-offs in klystron operation involving both the dimensions and operating voltages and therefore an accurate simulation is required to aid in the design of an optimised device.

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II. PRINCIPLE OF KLYSTRON OPERATION

With such a long history, the klystron is a well understood device with its own extensive literature (see for example [2,3] and more recently [4]). However, for convenience, the principle of operation of the reflex klystron (i.e. the form of the device considered in this paper) will be summarised here. A stream of electrons (conventionally produced by a heated cathode electron gun) passes through a pair of metal grids which form part of a tuned cavity as shown in Fig. 1. The stream is subsequently reflected back along its original path by a negatively charged electrode. Random fluctuations in the beam current give rise to an oscillating

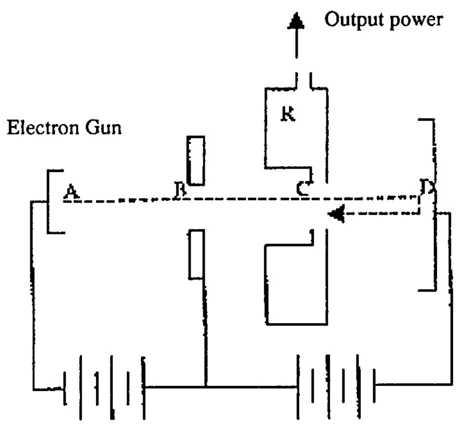

Fig .1. Schematic diagram of a reflex klystron (B is the electron accelerating anode, C the grids, R the resonant cavity and D the repeller electrode).

electromagnetic field in the cavity which results in a corresponding periodic potential difference between the grids. This potential variation has two effects. The first is to modulate the velocities of the electrons in the beam causing them to form up into bunches in the drift region and secondly if, after reflection by the retarding potential, the bunches return to the grids at the point in the cycle when the right hand grid is positive, power is transferred to the cavity. The electrons therefore constitute a feedback mechanism to the cavity and the conditions for oscillation to start spontaneously require the power transferred from the beam to the cavity to be at least equal to the combination of the losses that occur in the cavity and the

useful power delivered to an outside load (expressed in terms of the loaded Q or "quality factor of the system).

III. MICROMACHINED IMPLEMENTATION

At terahertz frequencies the typical cavity dimensions in a reflex klystron are determined by the wavelength λ of the radiation i.e. around 300 μm. A further critical dimension is the distance between the grids which must be $< \lambda/10$ to ensure that there is a very small voltage phase change as an electron bunch passes through i.e. the "transit time limit. It is these small feature sizes that make the manufacture of THz klystrons by conventional machining very difficult, especially as the metal surfaces require a high quality surface finish in order to reduce electrical losses to a minimum. On the other hand, the required dimensions are well within those obtainable by micromachining which also results in a high quality surface finish. This implementation of the klystron also takes advantage of another development of micromachining, the silicon cold cathode field emission tip. (Fig 2) [5,6,7]

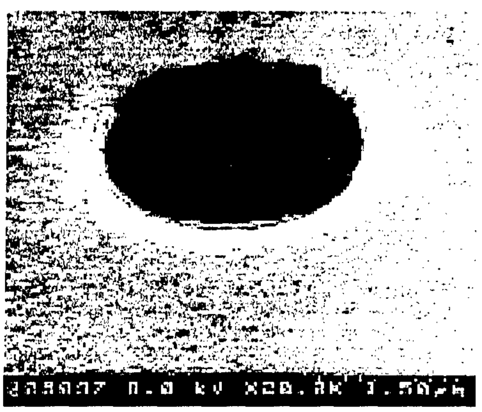

Fig. 2. A micromachined silicon field emission tip.

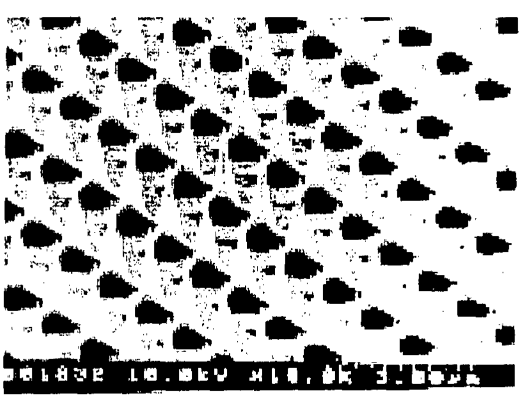

Fig. 3. An array of Si field emitter tips

Arrays of these electron emitting tips (Fig. 3.) are capable of producing higher beam current densities than heated filaments and at significantly lower temperatures. This low temperature operation is essential if ultra-thick photoresists are used to form the resonant cavities and it also relaxes the vacuum requirements. Field emitter arrays developed for plasma display purposes have been shown to have an operating lifetime of up to 1000 hours. The construction of a micromachined device is shown in Figure 4.

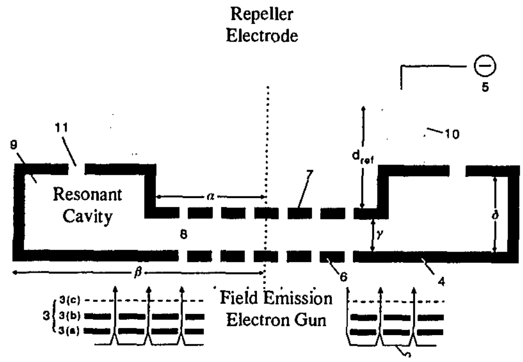

Fig. 4. Proposed construction of a micromachined klystron

IV. MODELLING

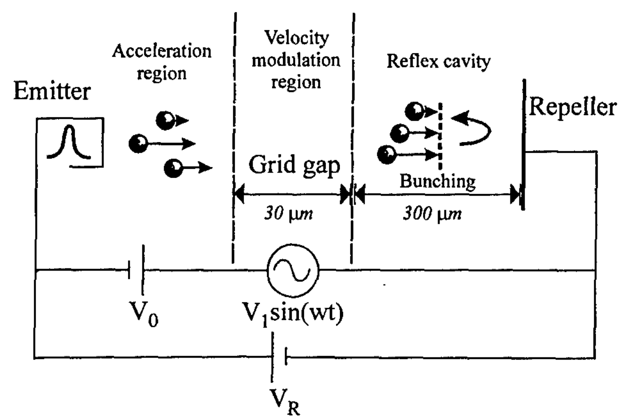

Fig. 5. Diagram of the 1-D geometry used for the physical simulation.

Figure 5 shows the structure that has been used for the modelling in this work. The electron beam is emitted from the cold cathode structure on the left and is assumed to have a Gausian distribution of velocities. The voltage V_0 applied to the field emission tips is taken to be 80V. The periodic potential difference generated between the grids by the electromagnetic field in the cavity is simulated by applying a periodic potential difference ($V_1\sin(\omega t)$) between them This is in fact a very good approximation because for the high Q cavities, which are necessary for the operation of these devices, any harmonics of the fundamental frequency are at a very low level. The resultant effect therefore is essentially a simple sinusoid. This implementation also avoids the necessity of electromagnetic field modelling and allows us to use a 1-D model. Some typical dimensions are shown in the figure

but it is a simple matter to vary the grid spacing, repeller electrode position and the magnitudes of the applied voltages in order to study their effect on the device operation. The left hand grid in the figure is electrically earthed which, as far as the model is concerned, means that any electrons arriving from the direction of the repeller disappear from the particle list in the plane of this grid. The "wires" in the grids are accounted for by assuming that a certain fraction of the electrons (anything between 50% and 20%) are lost as they transit each grid. Carefully aligned grids will of course reduce the losses as electrons will only be lost as they pass through the first grid on which they are incident.

At the time of writing it is assumed that the electrons are in sufficiently low densities such that they have (i) a negligible effect on the potential distribution in the device and (ii) do not collide with each other. The main particle interactions in the Monte Carlo model are therefore those with the time varying fields and the physical structure.

On starting, the program assumes that the device is empty of electrons and that they are then supplied from the field emitter gun. The simulation must therefore be run for 2 or 3 cycles before a steady state is reached.

V. RESULTS

Figures 6 and 7 illustrate an electron bunch travelling back through the grids having been reflected by the repeller electrode. Figure 6 is a plot of charge density and Figure 7 of current, both as a function of position in the device. The double peak is a well known feature of the bunching process.

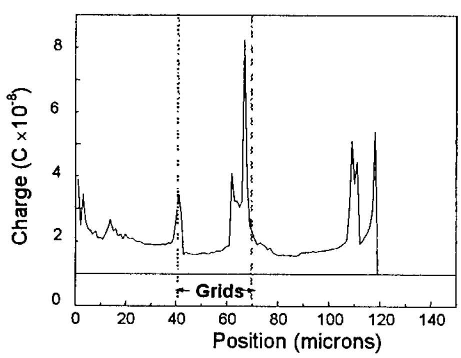

Fig. 6. Charge density as a function of position showing an electron bunch moving into the space between the grids after reflection at the repeller electrode.

The snapshot in time depicted in Figs. 6 and 7 represents the point where a charge bunch is just beginning to feed power into the cavity. Figure 8 shows the relationship between the current flowing through the device and the potential difference across it. It can be seen that the optimum phase relationship between current and voltage is not achieved under the conditions applied in this case but nevertheless the power transferred is estimated to be in the region of 1 mW (albeit for a frequency of only about 0.02 THz in this simulation). The figure does however serve to illustrate the behaviour of the device. A preliminary study has also been carried out on the best value to chose for the magnitude of V_0 and it would appear that the electron bunching is a maximum at around 15V which is the value used in the simulations shown here.

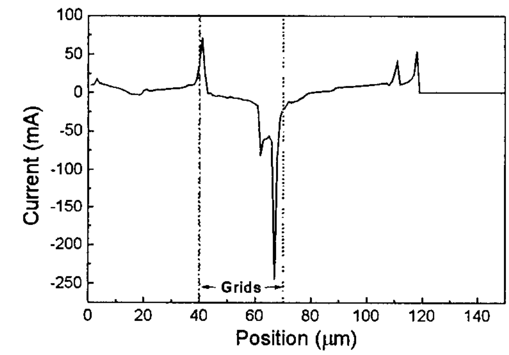

Fig.7. Particle current against position corresponding to Fig. 6. (Note; a negative current represents electrons travelling from right to left).

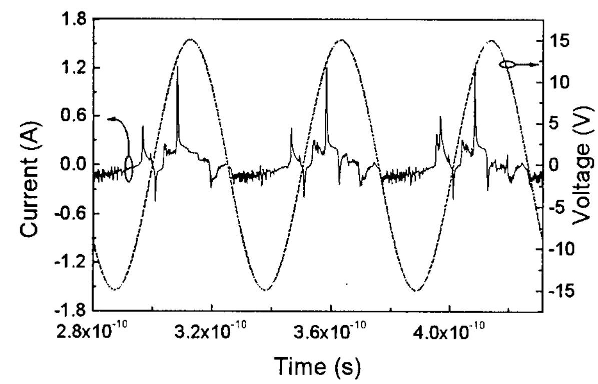

Fig. 8. Current and voltage for the simulated device.

VI. CONCLUSION

Recent developments in micromachining, particularly in cold cathode field emission arrays and ultra-thick photoresists have brought the klystron oscillator, operating at terahertz frequencies, a step closer to being realised. However there are still some formidable hurdles to overcome in arriving at an optimised device. There are a number of design parameters involving device geometries and operating conditions that can be varied but there is a strong interaction between them. An accurate physical model such as the one being developed here is therefore an essential design aid. This is particularly the case for these new devices where the fabrication technology is still under development.

ACKNOWLEDGEMENTS

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